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LHC IRQ Cryostat Engineering Design Review

March 12, 2001

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<http://tdpc02.fnal.gov/nicol/index.html>



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Acknowledgements

This work would not have been possible without the hard work and dedicated efforts of:

- Christine Darve
- Yuenian Huang
- Arnie Knauf
- Lucy Litvinenko
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- Tom Page
- Marsha Schmidt
- Tom Wokas
- George Zielbauer
- Jim Rife and all his technical staff



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Outline

- Evolution of the cryostat design.
- Vacuum vessel.
- Cold mass to cryostat interface and suspension system.
- Internal piping.
- Thermal shield.
- Final assembly concept and Q2P1 assembly.
- Q1 design concepts.
- R&D status and results.
- Current status of design and procurement.
- Concerns.
- Corrector mounting. (T. Page)
- Interconnect design. (T. Page)
- Q2a/b weld test results. (T. Page)

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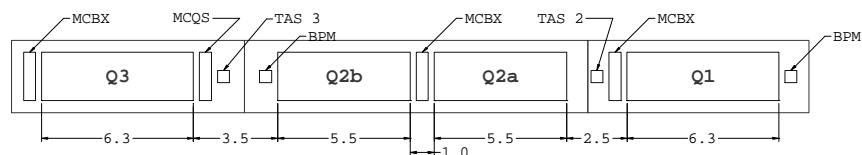
Evolution of the cryostat design...



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Triplet layout from optics



Notes:

1. Optics are V6.2.
2. All dimensions are in meters.
3. Magnets are shown in magnetic length.
4. From Fred - 6.3 m magnetic length becomes 6.604 m end plate to end plate.
5.5 m magnetic length becomes 5.804 m end plate to end plate.



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Heat load summary

Inner triplet heat loads - estimated				
Temperature level	50 to 75 K	4.6K	1.9K	Notes
Static heat loads (W)	220	0	18	1,2
Dynamic heat loads (W)	0	17	184	3
Total heat loads (W)	220	17	202	

Notes

1. Static heat load to outer shield = 140 W conduction through supports + 80 W radiation and residual gas conduction.
3. Static heat load to 1.9K = 12 W conduction through supports + 6 W radiation. Radiation estimate assumes $\epsilon=0.1$.
3. Dynamic heat loads based on nominal luminosity (N. Mokhov, June 2000).



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Estimated weights

Cold mass and final assembly estimated weights									
Magnet designation	Magnetic length (m)	OD (mm)	ID (mm)	Cold mass wt		Total wt		wt/support	
				(lb)	(kg)	(lb)	(kg)	(lb)	(kg)
Q2P1	5.5	416	70	11000	5000	18700	8500	5500	2500
Q1	6.3	490	70	20000	9091	29000	13182	10000	4545
Q2	5.5 x 2	416	70	23000	10455	38400	17455	7667	3485
Q3	6.3	490	70	21000	9545	30000	13636	10500	4773

Notes

1. Correctors are assumed to weigh approximately 1100 lb (500 kg).
2. Q2P1 total weight is actual.



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Piping parameters

Cooldown line							
Description	Fluid	OD (mm)	ID (mm)	P oper (bar)	P max (bar)	T (approx)	Flow (g/s)
Pumping line	Ghe	88.90	85.60	0.016	4.0	1.8 K	8.6
External heat exchanger outer shell	Lhe	168.28	162.74	1.3	20.0	1.9 K	0.0
External heat exchanger inner tube	Lhe	97.54	96.01	0.016	4.0	1.8 K	8.6
Cooldown line	Lhe	44.45	41.96	1.3	20.0	1.9 K	30.0
LHe supply (inside hx inner tube)	Lhe	15.88	13.39	0.016	4.0	1.8 K	8.6
4.5K supply	Lhe	19.05	15.75	1.3	20.0	4.5 K	1.1
4.5K return	Lhe	19.05	15.75	1.3	20.0	4.5 K	1.1
50-70K shield supply	Ghe	38.10	31.75	19.5	22.0	60 K	5.0
50-70K shield return	GHe	38.10	31.75	19.0	22.0	65 K	5.0



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Current IRQ alignment table

	AP Requirements	Mechanical Tolerances	Measurement and Survey Accuracy
1a) Single MQX cold mass			
Straightness H and V	Not limiting as long as ≤ 0 .	100 μ m/meter	Mechanical meas. Not limiting
Twist	Needs further study	1 mrad/5 meter	
1b) Single multilayer corrector field	Moved to 2b.		
2a) Relative alignment of MQX magnets in composite Q2			Mech. and stretch wire with survey equip.
Q2a/Q2b transverse alignment	500 μ m		100 μ m
Q2a/Q2b relative roll	1 mrad (rms)		100 μ rad (rms)
Q2a/Q2b relative pitch and yaw	100 μ rad	Mechanical tests scheduled starting in 2000	130 μ rad
2b) Relative alignment of corrector in a composite Q2 and Q3			Should be able to do with mech measurements
Corrector displacement	500 μ m		
Corrector roll	5 mrad		
3) Placement of composite coldmass into cryostat and relating magnetic axis to external fiducial			Only includes errors relating magnetic axis to external fiducial
Q1 Displacement transverse	300 μ m		180 μ m
Displacement longitudinal	~ 1 mm		
Roll angle	200 μ rad (rms)	Within limits, correctable if adjustments made to cryostat jacks, if fiducials are stable.	100 μ rad (rms)
Pitch/Yaw			130 μ rad
Q2 Displacement transverse	300 μ m		180 μ m
Displacement longitudinal	~ 1 mm		
Roll angle	100 μ rad (rms)	Mechanical tests scheduled for 2001	100 μ rad (rms)
Pitch/Yaw			130 μ rad
Q3 Displacement transverse	300 μ m		180 μ m
Displacement longitudinal	~ 1 mm		
Roll angle	100 μ rad (rms)		100 μ rad (rms)
Pitch/Yaw			130 μ rad

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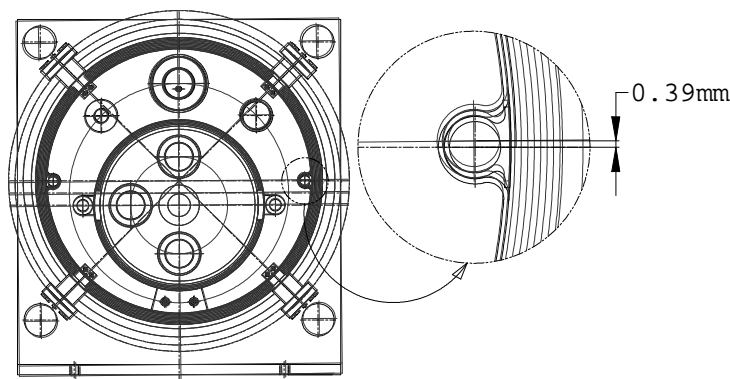
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Bellows offset resulting from magnet rotation during alignment



1 mrad rotation about beam center

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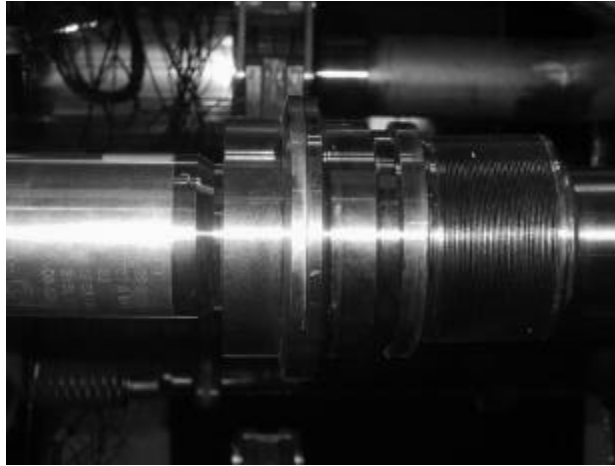
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Shield bellows connection to Q2P1 at MTF



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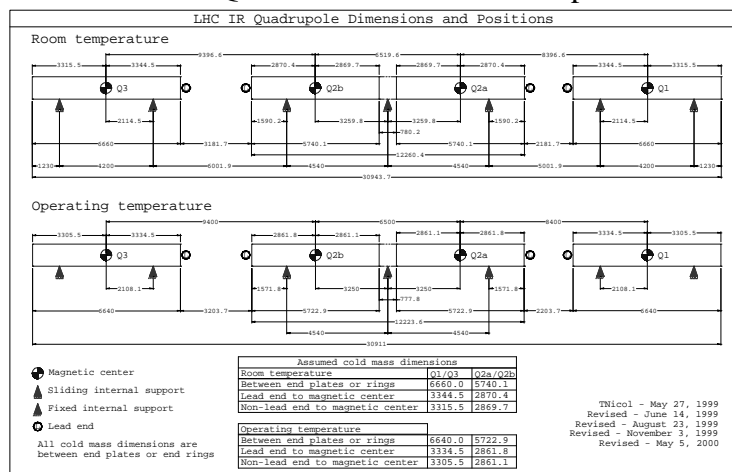
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Current IRQ dimensions and installed positions



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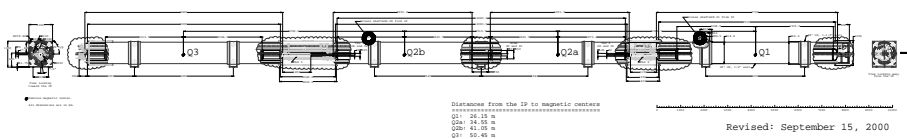


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Triplet layout

LHC IRQ Triplet Layout



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Triplet layout (detail of magnetic center locations)

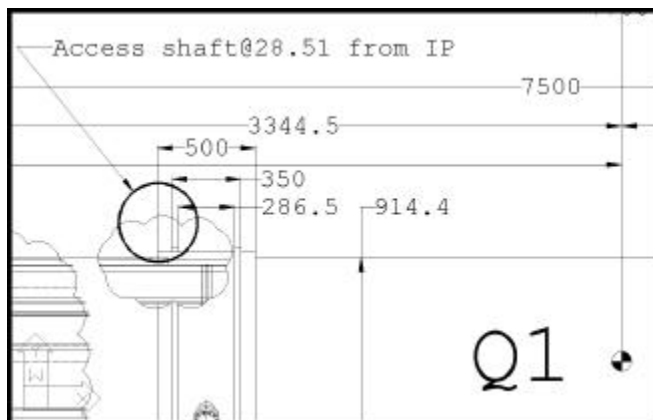
Distances from the IP to magnetic centers	
Q1:	26.15 m
Q2a:	34.55 m
Q2b:	41.05 m
Q3:	50.45 m



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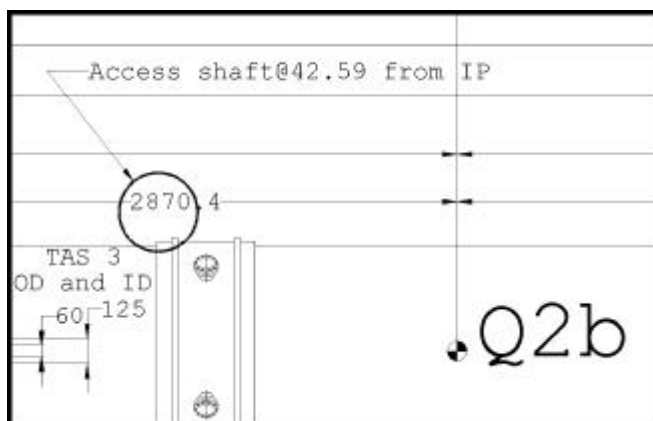
Triplet layout (detail of access shaft location)



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Triplet layout (detail of access shaft location)

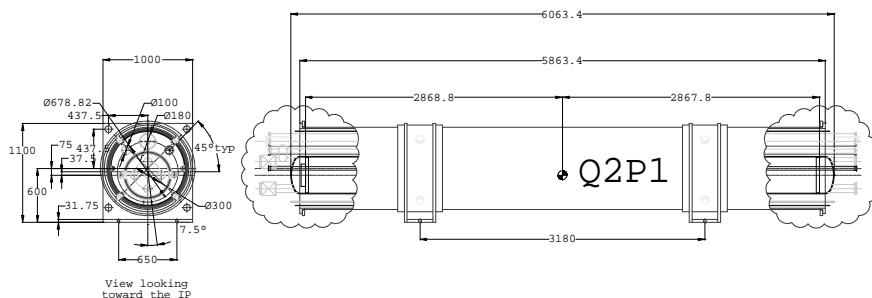




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First prototype layout (Q2P1)



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Engineering note goals

- Establishes the maximum allowable working pressure (MAWP) of the helium volume. The MAWP for Q2P1 is 175 psi (end dome limited) and for all production magnets will be 20 bar.
- Documents compliance with applicable piping code.
- Documents compliance of the vacuum vessel to applicable standards.
- Documents test results, material certifications, etc.

(Compliance is based on meeting the requirements of the Fermilab ES&H manual which is based on the ASME Boiler and Pressure Vessel Code and B31.3 Piping Codes.)

Available at: http://tdpc02.fnal.gov/nicol/lhc_irq_cryostat/engr_note/index.html

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<i>Cold mass weld coupon tests</i>	<i>A-1</i>
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Appendix C

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First prototype (Q2P1)





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Vacuum vessel...



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Vacuum vessel

- Multiple section design for better straightness.
- Design of vacuum bellows attachment modeled after LHC dipoles.
- Tie rods and vacuum relief valves are integrated into the vacuum bellows, not the vacuum vessel.
- Internal and external supports are coincident to minimize bending loads during shipping and handling.
- Support attachments are accessible from outside and provide a small amount of adjustment if necessary (not under vacuum).
- External supports (spherical sockets) compatible with CERN magnet supports.
- Fiducial holders can be located at any position adjacent to any support.
- Material used for Q2P1 was SA516 Grade 70.



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Vacuum vessel material specification for production magnets

2.0 Minimum material requirements.

- 2.1 The base material must have a minimum yield strength of 36,000 psi (248 MPa) with an elongation not less than 18%.
- 2.2 A standard Charpy impact test must be performed per ASTM E 29 at room temperature and at -50 °C on samples taken from each lot of material. Samples must be taken from the base material, heat-affected zone, and weld metal. If the material is supplied as plate, tests of the heat-affected zone and weld metal may be performed on samples taken from welds representative of those in the vacuum vessel assembly. Where applicable, samples must be tested in the transverse direction. A minimum energy absorption of 21 J/cm² and an average energy absorption of 28 J/cm² shall be obtained over each group of 3 samples.
- 2.3 The material must be weldable to 300 series stainless steel.
- 2.4 The material must be compatible with long-term operation at room temperature and internal pressure of 1.1×10^{-4} Pa.

3.0 Material certifications and test results.

- 3.1 Material certifications must be provided to the responsible Fermilab contract administrator for each heat of material and each lot of weld material. These reports must include the material designation, results of yield and tensile tests, and chemical analysis.
- 3.2 All material test results including, but not limited to, the Charpy impact tests, must be provided to the responsible Fermilab contract administrator. The sample for which test results apply must be identifiable using information contained in those reports.



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Q2P1 vacuum vessel





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Q2P1 vacuum vessel - exploded view



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Q2P1 vacuum vessel - support base



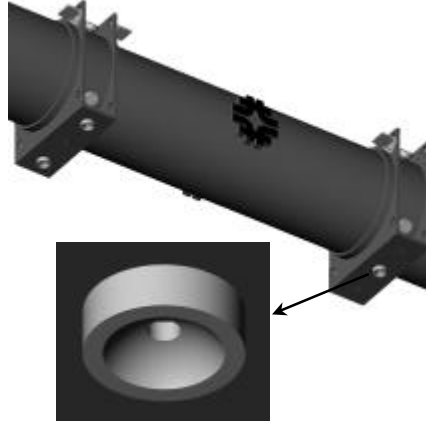


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Q2P1 vacuum vessel - tunnel interface

Force to move magnet	= 1.3 x weight
Force to move Q2P1	= 24,310 lb _f (11,050 kg)
Force to move Q1	= 37,700 lb _f (17,140 kg)
Force to move Q2	= 49,920 lb _f (22,690 kg)
Force to move Q3	= 39,000 lb _f (17,730 kg)
The vacuum load	= 20,000 lb _f (9,090 kg).
(Assumes a 57 mm radius, 90 mm diameter chord length spherical socket and no other restraint.)	



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Q2P1 vacuum vessel





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Cold mass, cold mass to cryostat interface,
and suspension system...



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Cold mass, cold mass to cryostat interface, and suspension system

- Support ring (“spider”) maximizes lateral stiffness of the assembly and provides room for the external heat exchanger assembly.
- Invar tie bars distribute axial load to all support rings.
- All support rings are identical regardless of magnet manufacturer. Different diameters are accommodated by the cold mass attachment lugs.

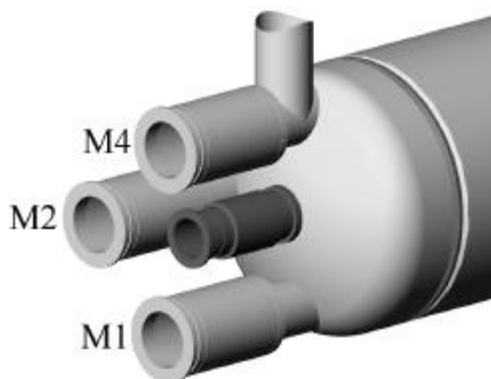


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Cold mass instrumentation locations (non-IP end shown)

M1: Magnet and corrector busses
M2: Thermometers, heaters, voltage taps
M3: No connection
M4: Empty



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Q2P1 cold mass





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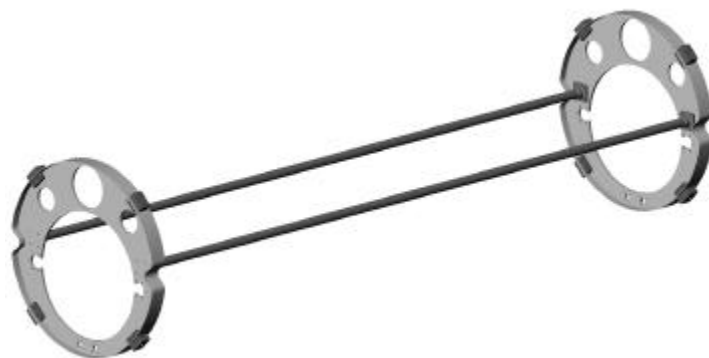
Q2P1 cold mass and support rings



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Q2P1 support rings and tie bars





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Support ring assembly



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Support ring to cold mass connection



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Support ring to cold mass connection



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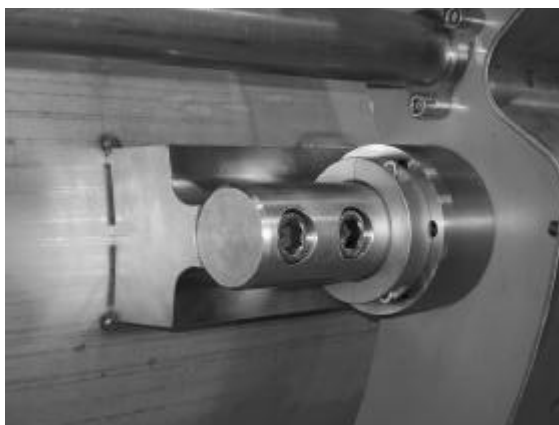
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Support ring to cold mass connection



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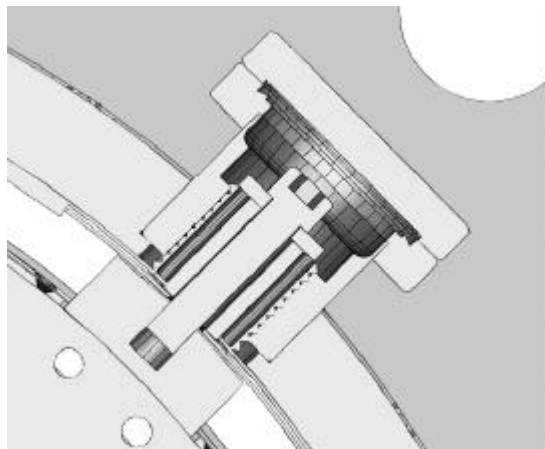
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Support ring adjusting mechanism



On Q2P1, a test of the adjustment mechanism after completion of the assembly enabled us to move the cold mass center ± 1.5 mm in any direction at each support location with little difficulty. We have opted to refine the pitch of the screws for production magnets to facilitate the process.

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Internal piping...



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Internal piping

- All of the internal piping is anchored axially within each cryostat.
- All pipes are located with respect to the cold mass using supports which result in no appreciable added heat load to 1.9K.
- All cryogenic supply lines are located with respect to their nominal positions to a precision of ± 2 mm.
- The piping supports define the horizontal and vertical pipe locations and provide lateral stability against bellows instability. Further, all interconnect bellows have integral liners to prevent bellows and piping failure due to instability.



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Q2P1 cold mass, support rings, and internal piping





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Q2P1 cold mass, support rings, and internal piping



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Internal piping support



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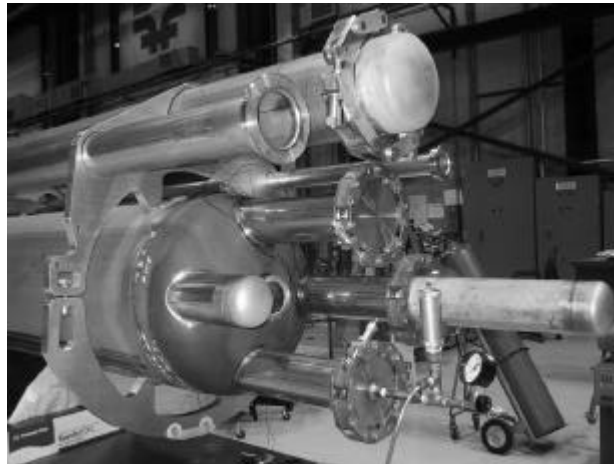
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Internal piping support on Q2P1



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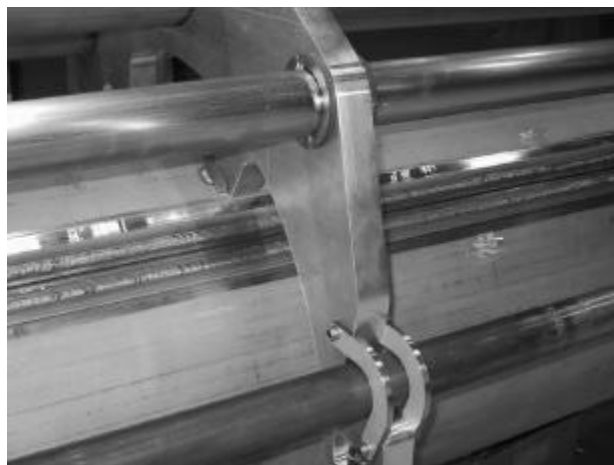
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Internal piping support on Q2P1



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Internal piping support on Q2P1 (no 4.5K intercept)



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Thermal shield...



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Thermal shield

- Multiple section design to minimize distortion during cooldown.
- Aluminum extrusion continuous along shield length.
- Aluminum to stainless steel transition required at each end of each extrusion for welding to interconnect bellows (Thevenet-Clerjounie diffusion bonded joints).
- Shield is anchored at one support and free to slide axially at the other(s).
- Shield on Q2P1 is instrumented to document temperature and thermal gradients.



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Q2P1 thermal shield assembly





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Q2P1 thermal shield assembly - exploded view



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Q2P1 thermal shield assembly

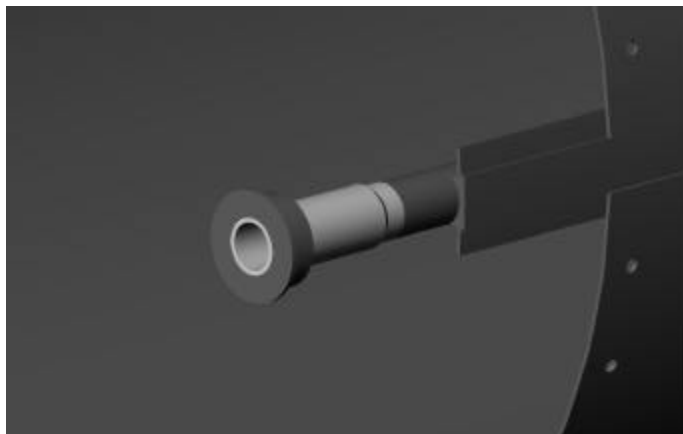




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Q2P1 thermal shield assembly - extrusion and transition joint



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Q2P1 thermal shield assembly - extrusion and transition joint



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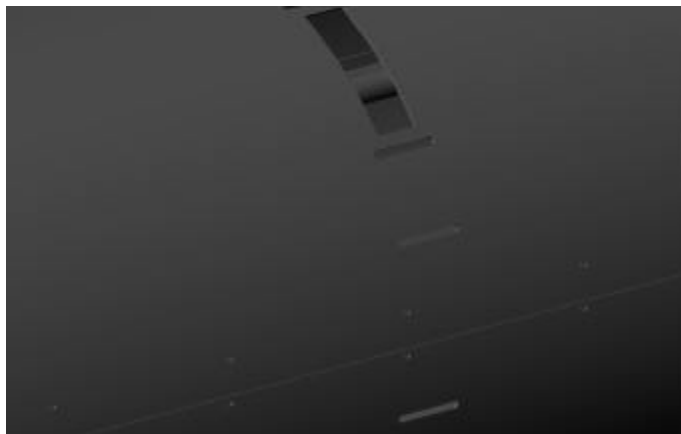
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Q2P1 thermal shield assembly - support location



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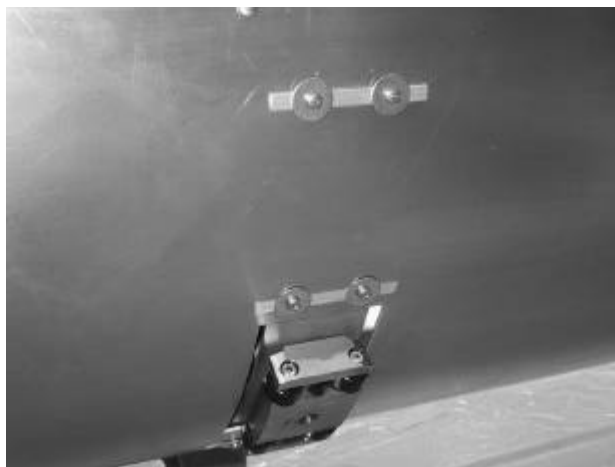
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Q2P1 thermal shield assembly - support location



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Final assembly concept...



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Final assembly concept

- The final assembly concept involves assembling the internal assembly on tooling compatible with an axial rail system, aligning it with the vacuum vessel, and rolling it into the vacuum vessel.
- After insertion is complete, the internal assembly is secured by bolts through the access ports in the vacuum vessel.



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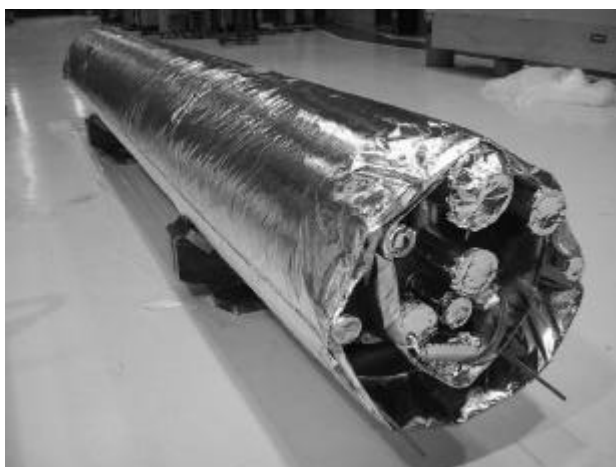
Q2P1 cold mass, internal piping, and thermal shield



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Q2P1 cold mass, internal piping, and thermal shield





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Final assembly concept



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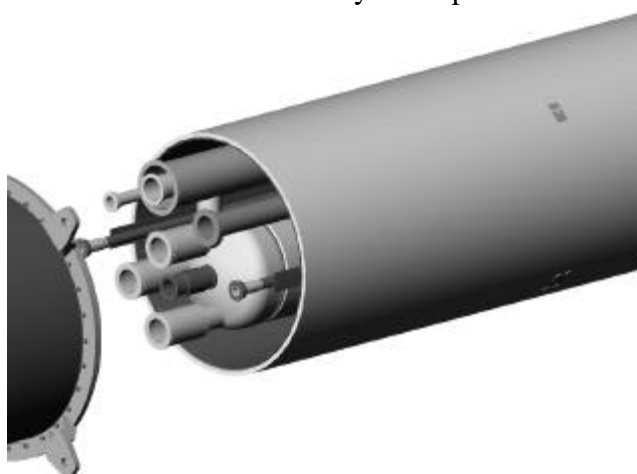
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Final assembly concept



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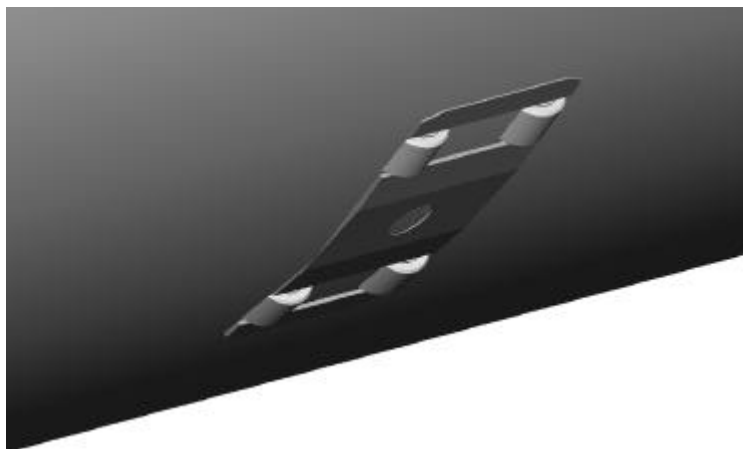
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Final assembly concept



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Final assembly concept (mind over matter)



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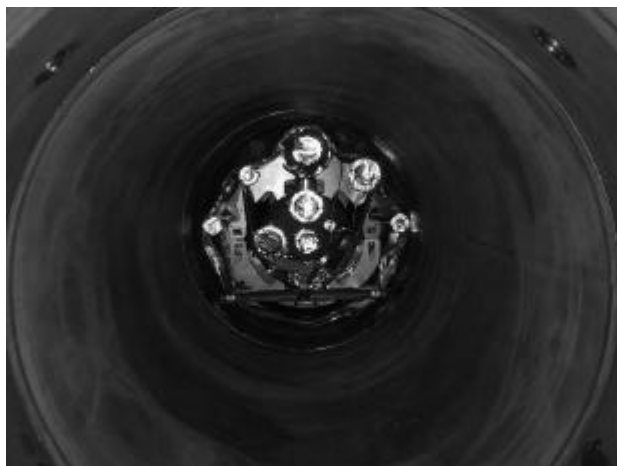
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Q2P1 assembly – birds-eye view



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Q2P1 assembly – non-IP end



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First prototype (Q2P1)



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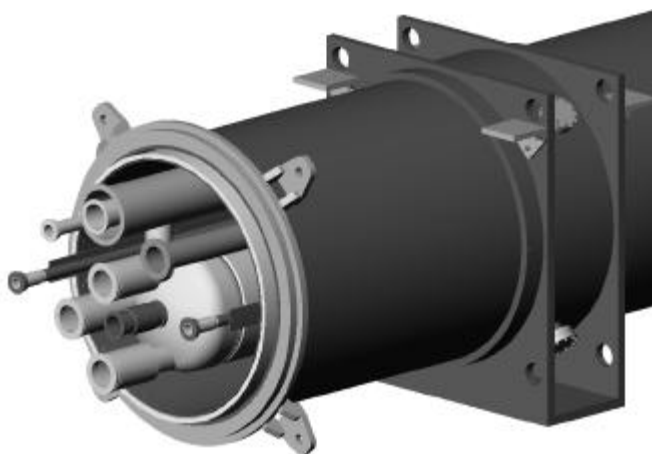
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Q2P1 assembly – non-IP end



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Q2P1 assembly – non-IP end



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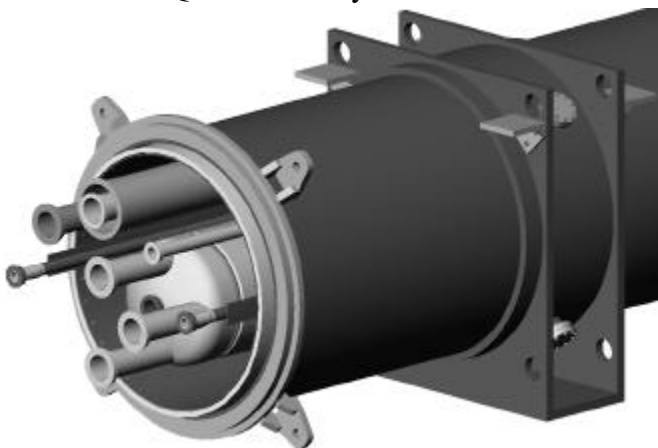
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Q2P1 assembly – IP end



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Q2P1 assembly – IP end



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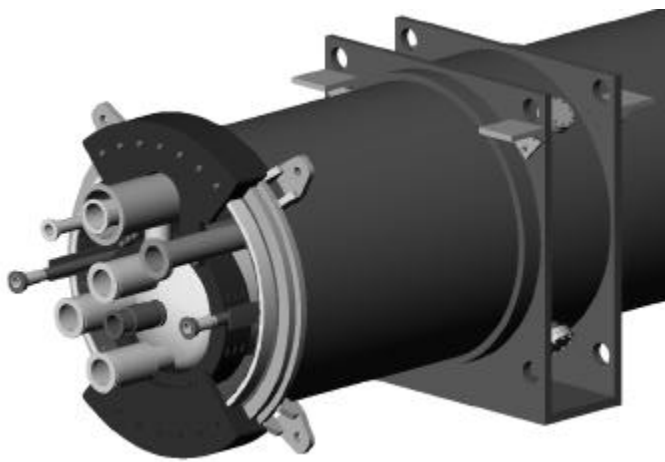
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Q2P1 assembly with shipping restraint



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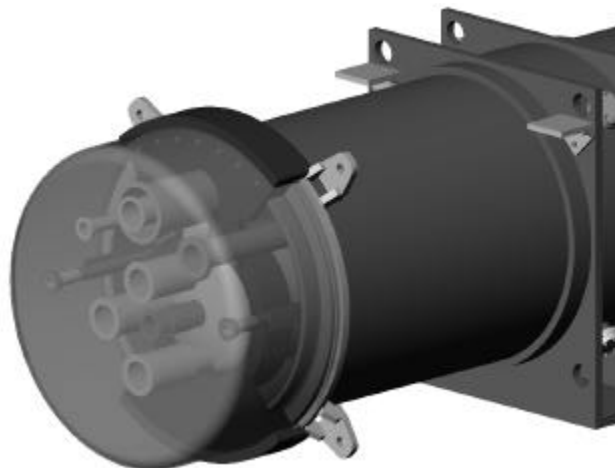
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Q2P1 assembly with shipping restraint and end cover



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Q1 design concepts...



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Q1 assembly – non-IP end



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Q1 assembly – non-IP end



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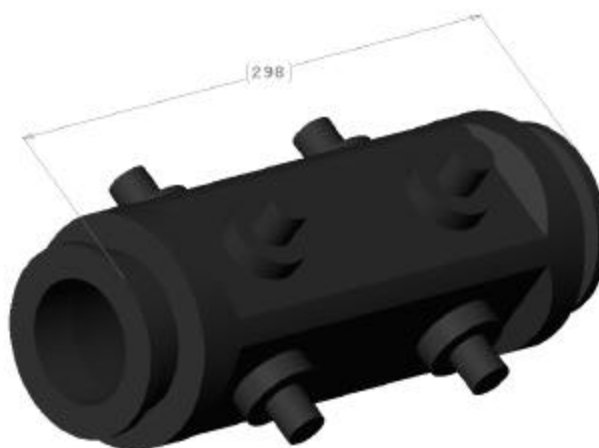
Q1 assembly – IP end



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BPM mockup

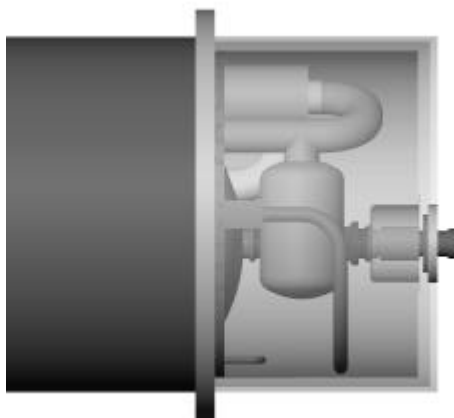




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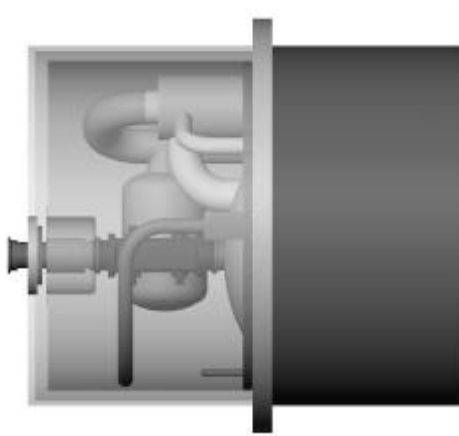
Q1 IP-end (right side when viewed from DFBX)



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Q1 IP-end (left side when viewed from DFBX)





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R&D status and results...



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R&D status

- Full scale heat exchanger feedbox, test modules, and turnaround have been fabricated, shipped to CERN, and tested.
- A small scale heat exchanger test has been completed on three potential heat exchanger material candidates.
- Two support rings have been fabricated and tested.
- Initial testing is complete on cold mass slide materials at low temperature and in vacuum.
- Testing of the weld connection between Q2a to Q2b is complete. (T. Page)
- Shipping loads will be evaluated on Q2P1 following cold testing.



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Full-scale heat exchanger test installation at CERN (SM18)



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Inner Triplet Heat eXchanger Test Unit

Goal: Validation of the LHC-IR Inner Triplet Quad cryogenic system

200 W for 30 m	Interaction Region @ Inner Triplet Typical Arc cooling loop
40 W for 107 m	

Proposition:

- Ø Larger (97/85 mm) corrugated OFHC copper HX (as tested for the small scale heat exchanger test)
- Ø Location outside and parallel to the Cold Mass

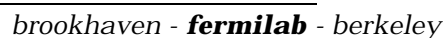
Experiment:

- Ø 30-m long thermal model designed at Fermilab, built in US industry, installed and tested at CERN
- Ø Measurement of the temperature distribution for various electrical loads simulating the LHC conditions and transient effects
- Ø Simulations of the nominal and the ultimate LHC conditions; check limitations of the inner triplet
- Ø Measurement of the thermal performances and validation of theoretical calculation

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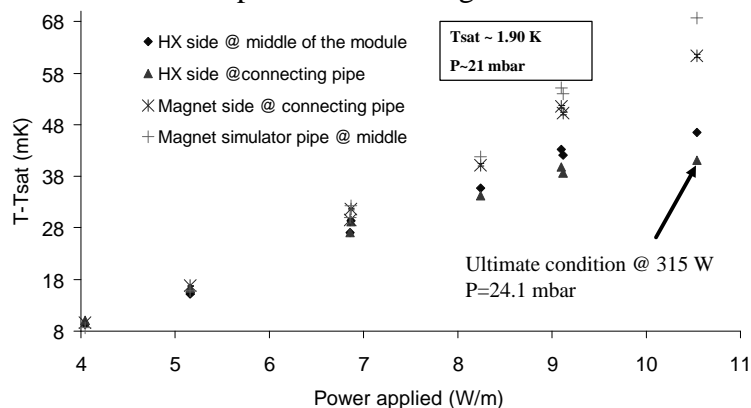
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Inner Triplet Heat eXchanger Test Unit



C/C: The difference of temperature on the heat exchanger interface < 50 mK

=> the design is validated with an increase of the connecting pipe section at each module interconnection.

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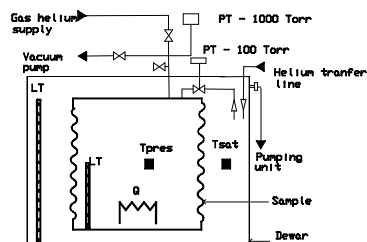


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Small Scale Heat eXchanger Test

Goal: Characterization of the IT-HXTU material properties (Kapitza Resistance)



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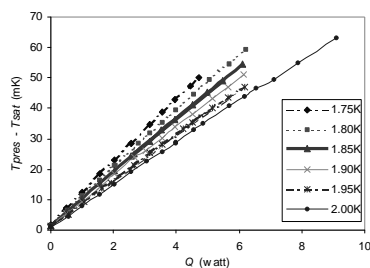
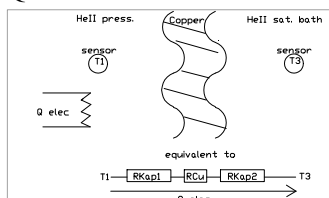
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Small Scale Heat eXchanger Test

Principle of measurement:

$$R_{th} = (T_{pres} - T_{sat}) / Q_{elec}$$



$$R_{th} = 2 \cdot R_{Kapitza} + R_{Cu} = \alpha (1/T_{pres}^3) + b$$

$$\alpha = \frac{2}{C_{Kapitza} \cdot S} \rightarrow R_{Kapitza}$$

$$\beta = \frac{e}{S \cdot C_{Cu}}$$

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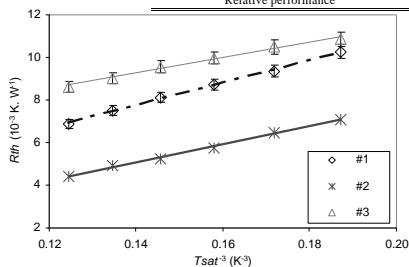
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Small Scale Heat eXchanger Test

Results:

Characteristics	#1 - OFHC	#2 - OFHC + HCl	#3 - Bronze
OD/ ID (mm)	97/86	97/86	123/101
Wall thickness (mm)	0.7	0.7	0.5
Corrugation depth (mm)	5	5	11
Corrugation pitch (mm)	12.4	12.4	11.7
Surface (cm ²) for one side	416	416	978
Shape of the corrugated pipe	Helical	Helical	Bellows
Surface treatment	None	Hydrochloric acid	None
Results			
CKapitza (W ⁻¹ K ⁻¹ m ⁻²)	893	1138	565
Kapitza conductance @ 1.85 K (W ⁻¹ K ⁻¹ cm ⁻²)	0.565	0.72	0.357
Thermal conductivity @ 1.85 K (W K ⁻¹ m ⁻¹)	88	88	2.4
Relative performance	Ref.	27%	-37%



C/C: The Kapitza conductance of OFHC copper treated with HCl is 30% larger than for the sample with no treatment. The bronze Kapitza is poor. The measurement of the Kapitza conductance of the OFHC copper permits to complete the study of the IT-HXTU.

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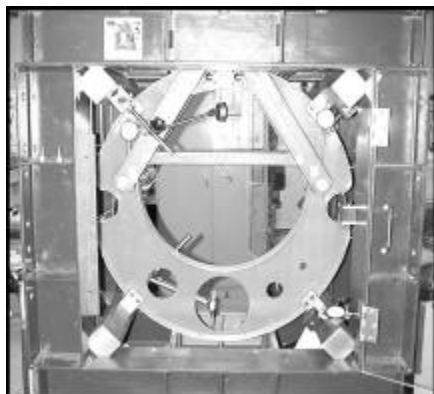


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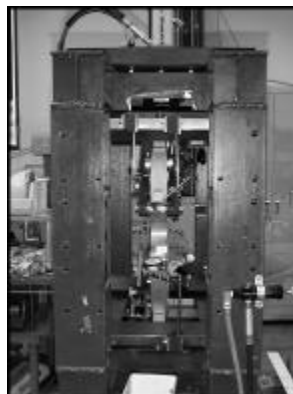
Support ring - run2

Goal: Validation of the support spider design and numerical analysis.
Measurement of the maximum load before break



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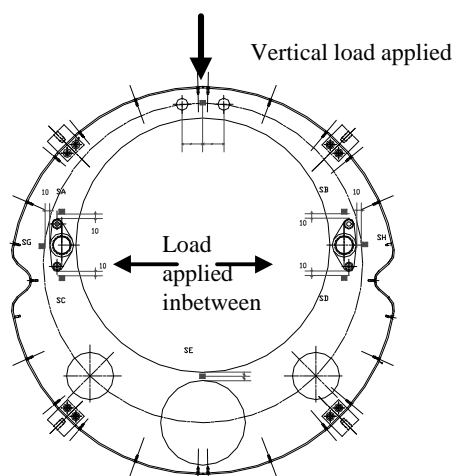
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Support ring test

Principle of measurement:
Location of strain gauges

Horizontal load applied



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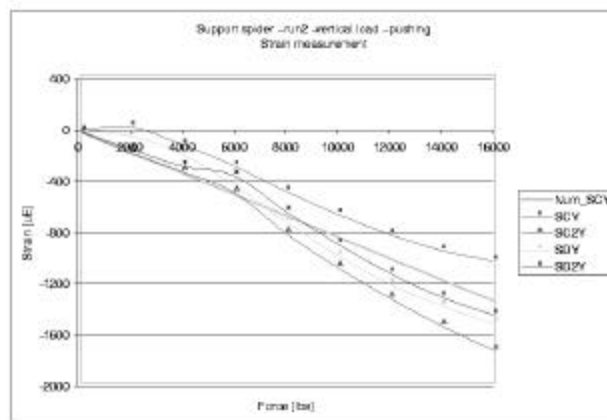
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Support ring test results

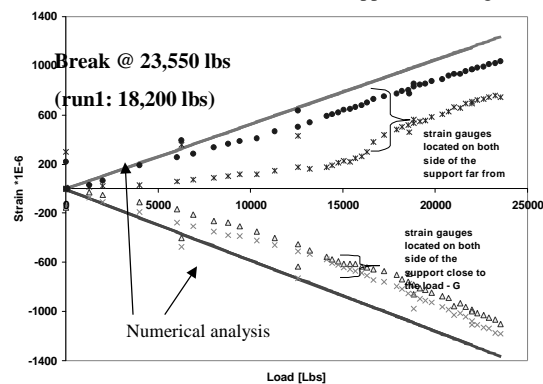


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Support ring test results

Measurement of the strain, Horizontal load applied, Pushing before break



C/C: The mechanical behavior of the LHC IRQ support ring has been validated.
The support (like in Q2P1) broke for a horizontal load as high as 23,550 lbs.



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Slide Material Test

Goal:

The purpose of the test is to measure the friction coefficient of several material combinations. The test is performed at nitrogen temperature and in vacuum.

This test will simulate the friction phenomena between pins (linked to the cold mass) and support spider bushing of the LHC Interaction Region Quadrupole. Hence the run permitted to choose of the bushing material.

Principle of measurement:

$$f = F1/F2$$

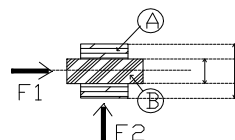
F1 = 0 to 1,000lbs (453Kg) ==> P1=0-1,000 PSI

F2 = 0 to 2,500lbs (1,133Kg) ==> P2=0-2,500 PSI

Material A: Vespel, Rulon LR, G fib., Teflon,

Utem 1000, Torlon, HDPE, DU, Bronze-Al, bronze.

Material B: SS - 304, Al, bronze, Bronze tube, SS - 304.

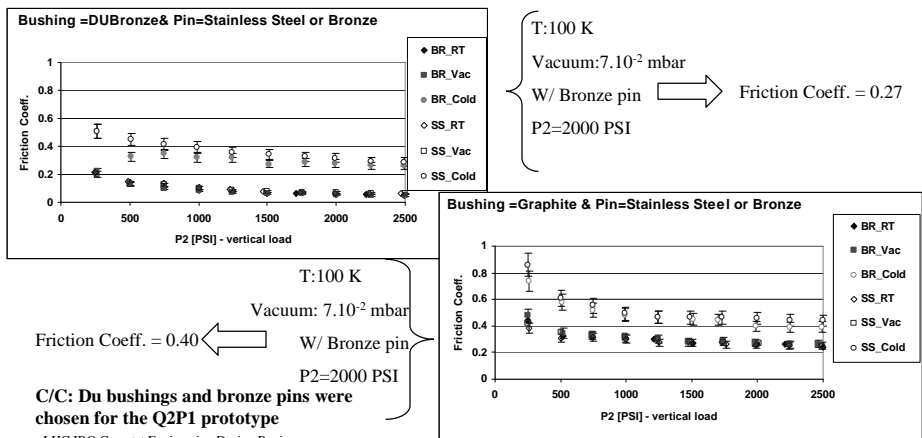


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Slide Material Test

Results:

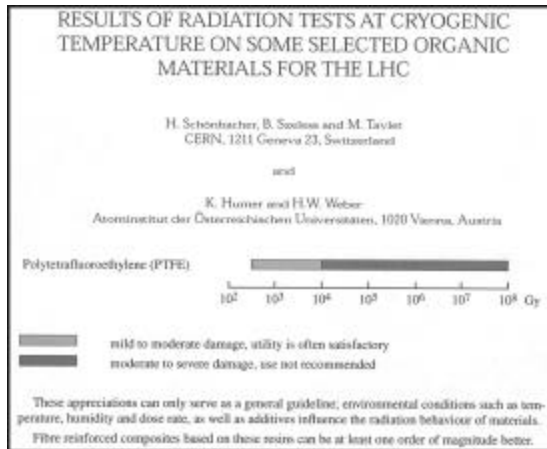




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Radiation damage potential to Teflon (in the support bushings)



Subject: Radiation numbers for cryostat
Date: Tue, 22 Aug 2000 11:38:16 -0500 (CDT)
From: Nikolai Mokhov <mokhov@fnal.gov>

Azimuthal variation of dose at such radii is much less than that for the coils. From our spring's results I found that the peak doses Dmax are only a factor of 1.5 (a factor of 2 at a couple of occasions) higher than the azimuthally averaged doses D. For the baseline luminosity and corresponding arithmetic (luminosity reduction over a store, 180 days per year etc. see my message of 02/12/99) with the above factor of 1.5, we get

	D (kGy/yr)	Dmax (kGy/yr)
24.07m from IP, 0.25m radius	1.5	2.3
28.25m from IP, 0.25m radius	3.5	5.3
33.26m from IP, 0.208m radius	5	7.5
37.80m from IP, 0.208m radius	6.5	9.8
42.34m from IP, 0.208m radius	9	13.5
48.34m from IP, 0.25m radius	5	7.5
52.53m from IP, 0.25m radius	5	7.5

For the above locations, I have also generated radial distributions of the azimuthally averaged dose ($2 < r < 25$ cm). Let me know if you need those plots.

Cheers,
Nikolai

$13.5 \text{ kGy/yr} \times 7 \text{ yr} = 9.5 \times 10^4 \text{ Gy}$ over a 7-year lifetime at nominal luminosity.

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Current status of design and procurement...



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Design and order status

- A request for bids is out for all IR quadrupole cryostat vacuum vessels. Bids are due back March 14, 2001.
- The design and drawing extrapolation from Q2P1 to all other cryostat components for Q1, Q2, and Q3 is 90% complete.
- The interconnect piping and bellows designs are complete.
- We are planning to use CERN dipole vacuum bellows and solid sleeves to adapt to the various interconnect lengths.
- Final assembly tooling is either on order or has been received. Setup will begin in spring 2001.



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Concerns

- Interfaces over which Fermilab does not have sole control need to be defined, especially for the BPM, cold-to-warm transition, and beam tube.
- Instrumentation port needs, e.g. production thermometry, BPM connectors, etc. are unknown.
- Uncertainties still exist in the lattice which will affect interconnects, details of magnet ends, etc.
- The effect of radiation on the cold mass slide material is not known.
- The mode of shipping is unknown and the effects on the completed magnet are untested.
- Overall cryostat performance is untested. This will be remedied, in part, with completion of the testing of Q2P1 in a few weeks.